EVALUATION OF THE EFFECT OF HEMP FIBERS ON THE PERFORMANCE PROPERTIES OF DENIM FABRICS

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The aim of this study has been to investigate the potential of using hemp fibers in denim fabric structures as a sustainable alternative to traditional cotton. For this purpose, a total of 12 different types of denim fabric structures were produced, including reference and hemp-based denim fabrics, as well as flax-based fabrics to enrich the study. In the production of denim fabrics, traditional and organic cotton ring-spun yarns were used in the warp, while traditional cotton, organic cotton/bamboo/flax, and organic cotton/bamboo/hemp hybrid yarns were used in the weft direction. The air and water vapor permeability, antibacterial activity, surface resistance, and fastness properties of the produced denim fabric structures were investigated comparatively using statistical analysis methods. Upon examining the results, contrary to expectations, the air and water vapor permeability of the fabrics containing flax and hemp were found to be lower than that of the reference fabric. Additionally, all types of fabrics produced were found to exhibit no antibacterial activity against the tested organism *Escherichia coli* (ATCC 25922 gram-negative bacteria). When the fastness results (light, crocking, laundering, water, and perspiration) were evaluated, it was observed that both flax- and hemp-containing denim fabric samples demonstrated the same performance as the reference fabrics, and all the developed denim fabric structures met industrial requirements.

Keywords: denim fabric, bamboo, flax, hemp, ecologically conscious design, antibacterial activity

INTRODUCTION

Climate change poses a serious threat to textile fibers. Studies have demonstrated how rising temperatures, droughts, and other severe weather conditions impact the availability of raw materials for the textile industry. While textile fibers are vulnerable to climate change, they also contribute to global warming.[1,2] Cotton, which currently accounts for 26% of global clothing production, has recently come under scrutiny due to its declining yield and fiber quality, both of which are exacerbated by climate change.[3-5] Additionally, cotton's environmental impact is significant, largely due to the excessive amounts of water, fertilizer, and pesticides used in its cultivation.[3,6-11] The rise in temperature and uncertain rainfall patterns affect crop duration, induce pest populations, and enhance evapotranspiration. Cotton production requires between 7000 and 29,000 L of water for every 1.0 kilogram. Excessive use of pesticides and fertilizers alters the quality of the water and soil, in addition to affecting the biodiversity of the land and its surroundings.[3,12-14] In response to these challenges, the fashion industry is increasingly exploring alternative fibers that could potentially reduce cotton's dominance in textile production.[1,15]

The primary issues with cotton are the opposite of the advantages of hemp, a historically used bast fiber.[1] Its cultivation process is environmentally friendly, as it grows rapidly with little to no water consumption. It is also seen as a more cost-effective crop compared to cotton, since it does not require herbicides, pesticides, synthetic fertilizers, or GMO seeds.[10,16-19] Montford and Small's (1999) study found that hemp fiber is the fifth most biodiversity-friendly fiber among 25 crops. The same study also shows that cotton is ranked 17th and negatively affects biodiversity, while hemp fiber has a positive impact on it.[20] Moreover, hemp fiber is one of the most versatile fibers, with antibacterial,[21,22] durable,[23,24] and natural air-conditioning[25,26] properties. Apart from the benefits it has as a textile material, hemp is crucial for improving soil health by restoring essential nutrients and preventing erosion.[16,17,27,28] Consequently, hemp serves not only as a sustainable alternative to the most commonly used fibers, but also surpasses them in terms of climate change resilience. Therefore, it can be suggested as an excellent choice for the manufacturing of clothing.

The main objective of this study is to raise awareness of the potential use of hemp fiber in denim fabric structure by comparing some key performance characteristics with those of traditional cotton fiber. Additionally, flax-based denim fabric structures were also developed to enrich the study and broaden the scope of natural fiber alternatives. To achieve this, twelve different denim fabric samples were produced, utilizing 100% traditional and organic cotton ring-spun yarns for the warp, and hybrid yarns made from traditional cotton, organic cotton/bamboo/flax, and organic cotton/bamboo/hemp blends for the weft. In these blends, bamboo fiber was incorporated due to its natural antibacterial properties, high breathability, and contribution to fabric softness, thereby enhancing both the functional and sustainable aspects of the denim structures. The air and water vapor permeability, antibacterial activity, surface resistance, and fastness properties of the produced denim fabric structures were investigated comparatively using statistical analysis methods.

EXPERIMENTAL

Materials

In this study, SEM images of the fibers used in denim fabric production are provided in Figure 1. The characteristics of the fibers used in denim fabric manufacturing are listed as follows: traditional cotton (C, length: 28.00 mm, fineness: 0.18 tex, strength: 30.83 cN/tex, elongation: 5.26%, Şanlıurfa province, Turkey), organic cotton (O, length: 27.85 mm, fineness: 0.18 tex, tenacity: 30.45 cN/tex, elongation: 5.25%, Akkucak Tekstil San. Tic. Ltd. Şti., Turkey), bamboo (B, length: 38.00 mm, fineness: 0.13 tex, strength: 25.90 cN/tex, elongation: 11.60%, TENBRO, China), flax (F, length: 33.00 mm, fineness: 0.33 tex, strength: 89.01 cN/tex, elongation: 2.80%, Leon VanDeCasteele, Belgium), and hemp fibers (H, cottonized hemp, length: 33.00 mm, fineness: 0.39 tex, strength: 45.00 cN/tex, elongation: 2.60%, La Chanvrière, France) as sheath fibers, and elastane (E, Lycra®, fineness: 7.80 tex, tenacity: 9.23 cN/tex, elongation: 520%, Lycra, UK) and polyester (P, T400®, fineness: 5.50 tex, tenacity: 35.35 cN/tex, elongation: 24.00%, Lycra, UK) as core component. Additionally, the chemicals used in the production of denim fabric structures included starch (Cottonal KS-Royal AVEBE U.A., Holland) as a sizing agent, salt as affinity agent, Glissofil Extra (Royal, AVEBE U.A., Holland) as a cross-linker, caustic soda (Likit Kimya San. ve Tic. A.Ş, Turkey) as a bleaching aid agent and impurity remover, indigo dye (DYSTAR Indigo Vat 40%) as a colorant, neutralizing acid and buffering agent (AKASIT PFC, Akkim Kimya, Turkey) as a pH regulator in the washing process, and polyethylene emulsion (REPELLAN NEU, Pulcra Chemicals, Germany) as chemical finish agent.

Methods

Fabrication of denim fabric structures

Twelve different types of denim fabric structures were developed to demonstrate the potential use of hemp fiber in denim fabrics. In the warp, traditional and organic cotton ring-spun yarns were employed, while the weft consisted of hybrid yarns comprising traditional cotton, organic cotton blended with bamboo and flax, and organic cotton blended with bamboo and hemp. The spinning parameters of the yarns were as follows: for the weft, Ne 18/1, twist per meter (T/m) 760, twist coefficient (ae) 4.50, Lycra draft 3.60, and T400 draft 1.10; for the warp, Ne 14/1, T/m 560, and ae 3.75. All denim fabric structures were woven using a dobby loom (Picanol Optimax-i 4R-220, Belgium) with a 3/1 Z twill weave pattern and 20 picks/cm density. Following weaving, the denim fabrics were applied to various finishing processes, including singeing (flat for the front face and tangent for the back face), washing (at 60 °C with a pH range of 5–7.5), chemical finish with a polyethylene emulsion to enhance seam non-slip properties, and sanforizing (at 130 °C and 40 m/min). Except for the twelve different weft yarns, all other materials and production parameters for the denim fabric structures were kept consistent. The characteristics and notation of the produced denim fabric structures are summarized in Table 1.

Characterization

Fabric analysis

To evaluate and compare some key performance characteristics of the developed denim fabric samples, the following analyses were carried out. Before the analysis, all samples were conditioned for 24 hours under standard atmospheric conditions of 65 ± 2% relative humidity and 20 ± 1 °C, in accordance with the ISO 139:2005 requirements. Each test was run in three replicates, and averages of the test results were calculated. Error bars were calculated using the coefficient of variation. Air permeability (ASTM D737 04) and water vapor permeability (BS7209-1990) of the denim fabric samples were measured using DVT HG and TESTEX TF165A, respectively. The antibacterial activity of the denim fabrics was measured according to AATCC 100:2019 standards with the test organism *Escherichia coli* (ATCC 25922 gram-negative bacteria). Surface resistance of the denim fabrics was analyzed using Gigalab-Evo. The developed denim fabric samples were analyzed for fastness properties, including light (ISO 105 B02) using SDLATLAS XENOTEST 150S+, crocking (ISO 105 X12) using SDLATLAS M238BB, washing (ISO 105 C06) using SDLATLAS M228 B, water (ISO 105 E01) and perspiration (ISO 105 E04) using a James Heal Tester (ISO).

Statistical analysis

With the use of Design Expert Software 13, the study's data were statistically analyzed using a multilevel categorical design. A two-way analysis of variance (ANOVA) with a 95% confidence interval (CI) was used to evaluate the significance of the sheath fiber and core component types.

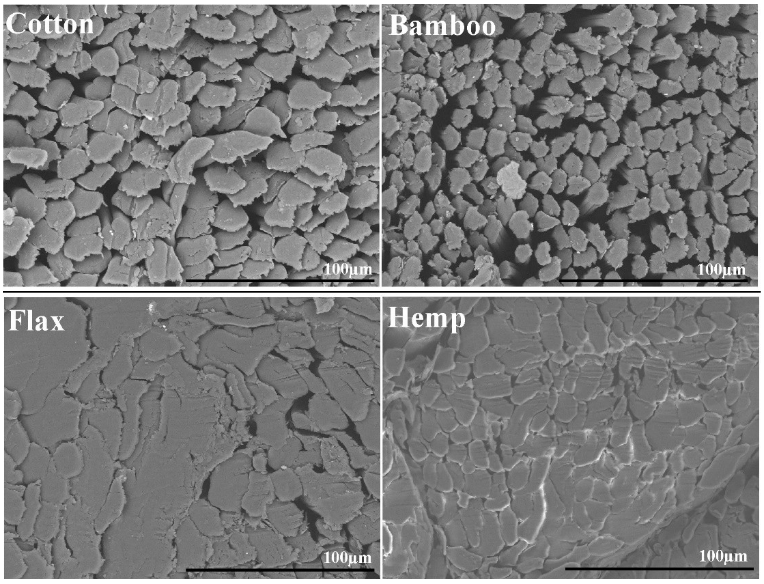

Figure 1: SEM images of the fibers used in denim fabric production

Table 1
Characteristics and notation of the produced denim fabric structures

Fabric type	Fabric composition	
	Warp yarn	Weft yarn
C	100.00% traditional cotton	100.00% traditional cotton
CE		93.40% traditional cotton + 6.60% elastane
CP		84.80% traditional cotton + 15.20% polyester
CEP		78.20% traditional cotton + 6.60% elastane + 15.20% polyester
OBF	100.00% organic cotton	47.00% organic cotton + 33.00% bamboo + 20.00% flax
OBFE		43.90% organic cotton + 30.82% bamboo + 18.68% flax + 6.60% elastane
OBFP		39.86% organic cotton + 27.98% bamboo +16.96% flax + 15.20% polyester
OBFEP		36.75% organic cotton + 25.81% bamboo + 15.64% flax + 6.60% elastane + 15.20% polyester
OBH		47.00% organic cotton + 33.00% bamboo + 20.00% hemp
OBHE		43.90% organic cotton + 30.82% bamboo + 18.68% hemp + 6.60% elastane
OBHP		39.86% organic cotton + 27.98% bamboo + 16.96% hemp + 15.20% polyester
OBHEP		36.75% organic cotton + 25.81% bamboo + 15.64% hemp + 6.60% elastane + 15.20% polyester

The terms R^2, df, F, and p in the ANOVA table refer to the proportion of the variance for a dependent variable that is explained by an independent variable in a regression model, the degrees of freedom, variation between the sample means, and whether there is a significant difference between the sample means, respectively. Additionally, Duncan's multiple range tests were conducted at a 0.05 significance level using the SPSS-20 software package to determine the effects of subgroups.

RESULTS AND DISCUSSION

Air permeability

The statistical test results (ANOVA and Duncan) and air permeability findings for the produced denim fabric samples are presented in Tables 2 and 3, and Figure 2, respectively. The explanatory power of the model, represented by the R^2 value, was determined to be 88.26%. According to the ANOVA table, there was a significant difference between sheath fiber type, core component type, and the interaction of these two independent variables, with $p < 0.05$. The core component type was the most influential independent variable on air permeability (mm/s), contributing by 51.76%.

Table 2
ANOVA statistics for air permeability values

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	3487.44	88.26	11	317.04	16.41	< 0.0001
Sheath fiber type	1053.26	26.66	2	526.63	27.25	< 0.0001
Core component type	2045.00	51.76	3	681.67	35.28	< 0.0001
Sheath fiber type *core component type	389.18	9.85	6	64.86	3.36	0.0152
Error	463.76	11.74	24	19.32		
Corrected total	3951.20	100.00	35			

Table 3
Duncan's multiple range test (p=0.05) for air permeability of denim fabrics *versus* sheath fiber type or core component type

Air permeability	N	Subset 1	Subset 2
Sheath fiber type			
C	12		72.19
OBF	12	60.06	
OBH	12	61.52	
Sig.		0.42	1.00
Core component type			
R	9		71.85
E	9	58.59	
P	9		72.27
EP	9	55.66	
Sig.		0.17	0.84

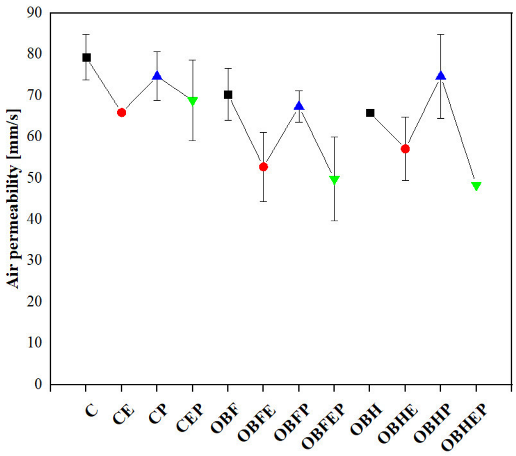

Figure 2: Air permeability results of the developed denim fabric samples

According to the Duncan test results, the C sheath fiber type significantly differed from both OBF and OBH. However, no significant difference was found between OBF and OBH. Among the core component types, a significant difference was observed between R and E, as well as between R and EP, but no significant difference was found between R and P or between E and EP.

When fabrics without core components were considered, the reference fabric (C) exhibited 11.34% higher air permeability than the flax-based fabric (OBF) and 16.87% higher than the hemp-based fabric (OBH). This unexpected outcome could be attributed to the fabric density and moisture absorption properties of the fibers. The blending of bamboo, flax, or hemp likely created a tighter weave or increased fabric density, which reduced the space between yarns and restricted air passage.[29] Additionally, the higher moisture absorption capacity of bamboo, flax, and hemp fibers might have caused swelling, further decreased pore sizes, and limited airflow. Regarding the effects of core component usage, elastane and dual-core components caused a 13.34% to 29.17% reduction in air permeability. In contrast, polyester either resulted in a 4.17% to 5.80% decrease or a 13.33% increase in air permeability. This could be due to the shrinkage caused by the core components, resulting in a more compact fabric structure, with reduced gaps between the yarns.[30]

Water vapor permeability (%)

The statistical analysis (ANOVA and Duncan) and water vapor permeability results of the produced denim fabric samples are presented in Tables 4 and 5, and Figure 3, respectively. The R^2 value for water vapor permeability was determined to be 88.03%. The ANOVA statistics demonstrated that all independent variables had a statistically significant effect ($p<0.05$) on water vapor permeability. The most effective independent variable on fabric water vapor permeability properties was the sheath fiber type*core component type (44.30%).

Table 4
ANOVA statistics for water vapor permeability values

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	8763.59	88.03	11	796.69	16.04	< 0.0001
Sheath fiber type	470.31	4.72	2	235.16	4.74	0.0185
Core component type	3882.84	39.00	3	1294.28	26.06	< 0.0001
Sheath fiber type *core component type	4410.44	44.30	6	735.07	14.80	< 0.0001
Error	1191.80	11.97	24	49.66		
Corrected total	9955.38	100.00	35			

Table 5
Duncan's multiple range test (p=0.05) for water vapor permeability of denim fabrics *versus* sheath fiber type or core component type

Water vapor permeability	N	Subset 1	Subset 2	Subset 3
Sheath fiber type				
C	12	180.98		
OBF	12		189.00	
OBH	12		188.23	
Sig.		1.00	0.79	
Core component type				
R	9	178.09		
E	9		192.02	
P	9			199.94
EP	9	174.24		
Sig.		0.26	1.00	1.00

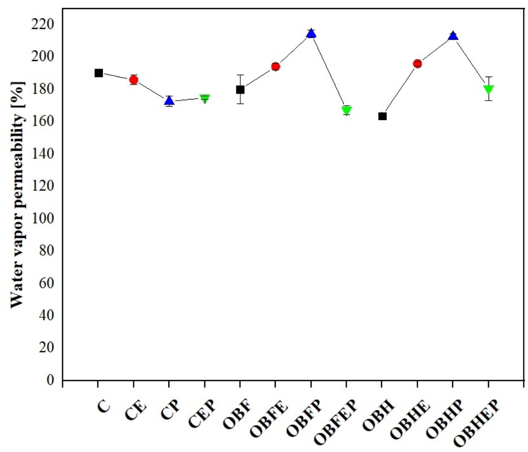

Figure 3: Water vapor permeability results of the developed denim fabric samples

The Duncan statistical analysis results revealed that the reference fabric (C) was significantly different from the flax-based fabric (OBF) and the hemp-based fabric (OBH), but no significant difference was found between OBF and OBH. Among the core component types, no significant difference was found between R and EP, whereas significant differences were observed between R, E, and P or EP, E and P. When comparing fabrics without core components, the reference fabric has the highest water vapor permeability (C: 190.50±1.70%), while the hemp-based fabric (OBH: 163.66±1.25%) has the lowest. These results were thought to be due to the same reasons noted for the air permeability results. In terms of the effect of the core material, no apparent trend in values was noticed.

Antibacterial activity (%)

The antibacterial activity results of the developed denim fabric samples are presented in Table 6. The *Escherichia coli* (ATCC 25922) bacterial growth on the samples after 24 hours of incubation is shown in Figure 4. Statistical analysis could not be performed as there were no differences between the results of the test replications. CFU/mL refers to colony-forming units per milliliter, a measurement used to estimate the number of viable bacteria or fungal cells in a given sample. The initial bacterial concentrations (0 h contact time) for all samples ranged from 3.90×10^3 to 2.85×10^4 CFU/mL. After 24 hours of incubation, the bacterial count increased exponentially in all samples (ranging from 3.70×10^7 to 2.24×10^8).

Table 6
Antibacterial activity results of developed denim fabric samples

Sample notation	0 h contact time (cfu/mL)	24 h contact time (cfu/mL)	Antibacterial activity (%)	Antibacterial classification
C	2.23×10^4	2.25×10^8	0	Non-effective
CE	1.89×10^4	1.96×10^8		
CP	1.61×10^4	2.24×10^8		
CEP	1.89×10^4	3.70×10^7		
OBF	2.85×10^4	1.99×10^8	0	Non-effective
OBFE	2.83×10^4	1.62×10^8		
OBFP	3.90×10^3	2.07×10^8		
OBFEP	2.57×10^4	1.80×10^8		
OBH	2.54×10^4	2.28×10^8	0	Non-effective
OBHE	1.21×10^4	2.28×10^8		
OBHP	1.81×10^4	9.20×10^7		
OBHEP	7.90×10^3	1.88×10^8		

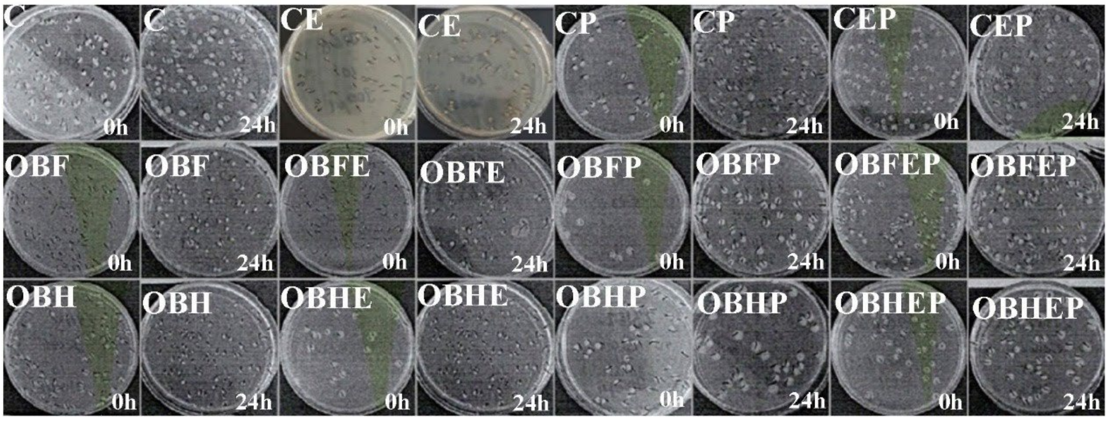

Figure 4: Bacterial growth of *Escherichia coli* after 24 hours of incubation

All the samples were classified as non-effective in terms of antibacterial activity. Although previous studies have highlighted the antibacterial activity of hemp fiber-based fabrics, the hemp-containing denim fabric samples produced in the current study did not exhibit any antimicrobial activity against the tested microorganism. There were several possible explanations for this occurrence. The first possible reason could be its effectiveness against other types of microorganisms rather than the specific bacterial species used in this study. Another possible explanation could be the use of industrial hemp fibers. During industrial processing, hemp fibers undergo retting, degumming, and bleaching. These processes might strip away many of the natural bioactive compounds, such as cannabinoids, alkaloids, and phenolic compounds, that are responsible for antibacterial activity, potentially reducing their effectiveness.[31,32]

Surface resistance

The developed denim fabric samples' statistical analysis (ANOVA and Duncan) and surface resistance results are provided in Tables 7, 8 and Figure 5, respectively. The R^2 value was found to be 62.44%. Based on the ANOVA results, sheath fiber type ($p > 0.05$) did not have a statistically significant effect on surface resistance results. In contrast, the core component type and the interaction between the sheath fiber type and the core component type ($p < 0.05$) were statistically significant. With a 36.80% contribution, the core component type was the most significant independent variable on surface resistance. The Duncan statistical analysis revealed no significant differences among sheath fiber types. However, EP was significantly different from R, E, and P within the core component types, while R, E, and P showed no significant differences among themselves. When evaluating fabrics without core components, the hemp-containing fabric exhibited the highest surface resistance value at 41.23±5.51 GΩ, whereas the reference fabric showed the lowest value at 35.70±5.19 GΩ. Although high moisture content typically reduces surface resistance by enhancing conductivity, hemp-containing fabrics exhibited contrary behavior, likely due to their intrinsic properties. The inherent rigidity and thickness of hemp fibers contributed to a denser fabric weave, which restricted moisture distribution across the surface.

Table 7
ANOVA statistics for surface resistance values (GΩ)

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	299.75	62.44	11	27.25	3.63	0.0040
Sheath fiber type	33.89	7.06	2	16.95	2.26	0.1266
Core component type	176.64	36.80	3	58.88	7.84	0.0008
Sheath fiber type*core component type	89.22	18.59	6	14.87	1.98	0.1086
Error	180.30	37.56	24	7.51		
Corrected total	480.05	100.00	35			

Table 8
Duncan's multiple range test (p=0.05) for surface resistance of denim fabrics *versus* sheath fiber type or core component type

Surface resistance	N	Subset 1	Subset 2
Sheath fiber type			
C	12	38.09	
OBF	12	35.80	
OBH	12	37.49	
Sig.		0.06	
Core component type			
R	9		38.43
E	9		39.43
P	9		37.07
EP	9	33.58	
Sig.		1.00	0.10

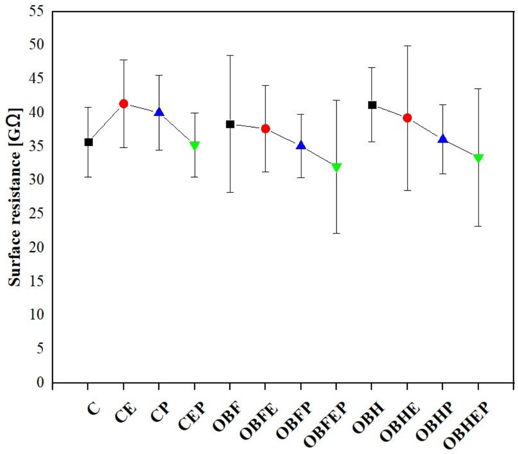

Figure 5: Surface resistance results of the developed denim fabric samples

This densification counteracted the expected facilitation of conductivity by moisture, leading to higher surface resistance despite the fiber's notable moisture absorption capacity. Regarding the effect of the core component used, regardless of the core component type, their usage increased surface resistance in the reference fabric, except for the CEP. Conversely, they decreased surface resistance in fabrics containing flax and hemp.

Color fastness to light and crocking

The color fastness results to light and crocking of the developed denim fabric samples are illustrated in Table 9. Statistical analysis could not be performed, as there were no differences between the results of the test replications. Color fastness to both light and crocking was the same in all samples. These results show that both the flax and hemp-based fabric samples exhibited the same performance as the reference fabrics. According to ASTM D6554: Standard Performance Specification for 100% Cotton Denim Fabrics, the minimum requirement for color fastness to light is 4 on the blue wool scale (ranging from 1 to 8).[33] The results in the table indicate that all samples achieved a value of 4-5, which complies with the standard. The minimum requirements for colorfastness to crocking are 3 for dry conditions and 1-2 for wet conditions on the grey scale (ranging from 1 to 5).[33] These results demonstrate that all developed denim fabric structures met industrial requirements.

Color fastness to laundering

The color fastness results to laundering of the produced denim fabric samples are shown in Table 10. Since there were no differences between the test replications results, statistical analysis was not conducted. Regarding color change, both OBF and OBH fabrics exhibited equivalent performance to the reference fabrics, achieving a grade of 4. Likewise, similar results were observed for staining across all denim fabric samples, with grades ranging from 3-4 to 4-5 depending on the adjacent fibers. As per the ASTM D6554 standard, the minimum requirement for colorfastness to laundering, in terms of both color change and staining on adjacent fibers, is 2 on the grey scale (ranging from 1 to 5).[34]

Table 9
Color fastness results to light and crocking of the developed denim fabric samples

Sample notation	Color fastness to light	Color fastness to crocking	
		Dry	Wet
C	4-5	3	1-2
CE	4-5	3	1-2
CP	4-5	3	1-2
CEP	4-5	3	1-2
OBF	4-5	3	1-2
OBFE	4-5	3	1-2
OBFP	4-5	3	1-2
OBFEP	4-5	3	1-2
OBH	4-5	3	1-2
OBHE	4-5	3	1-2
OBHP	4-5	3	1-2
OBHEP	4-5	3	1-2

Table 10
Color fastness results to laundering of the developed denim fabric samples

Sample notation	Color fastness to laundering						
	Color change	Staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
C	4	4	3-4	3-4	4	4	4-5
CE	4	4	3-4	3-4	4	4	4-5
CP	4	4	4	3-4	4	4	4-5
CEP	4	4	4	3-4	4	4	4-5
OBF	4	4	4	3-4	4	4-5	4-5
OBFE	3-4	4	3-4	3-4	4-5	4	4-5
OBFP	4	4	3-4	3-4	4	3-4	4
OBFEP	4	4	3-4	3-4	4	4	4-5
OBH	4	4	4	3-4	4	3-4	3-4
OBHE	4	4	4	3-4	4	4	4
OBHP	4	4	3-4	3-4	4	4	4-5
OBHEP	4	4	3-4	3-4	4	4	4-5

The results obtained demonstrate that all developed denim fabric samples performed above the required standards.

Color fastness to water

Table 11 shows the color fastness results to water of the developed denim fabric samples. There were no differences between the test replication results, hence statistical analysis was not performed. All samples exhibited high levels of color fastness to water, with ratings consistently ranging between 4 (good) and 4-5 (very good to excellent) on the grey scale for both color change and staining. This indicated that the tested materials maintained their color integrity well under wet conditions and showed minimal staining on adjacent fibers.

Color fastness to perspiration

The developed denim fabric samples' color fastness results to perspiration are displayed in Tables 12 and 13. Statistical analysis was not performed because the test replication results showed no differences.

Table 11
Color fastness to water results of the developed denim fabric samples

Sample notation	Color fastness to water						
	Color change	Staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
C	4-5	4-5	4-5	4	4-5	4-5	4-5
CE	4-5	4-5	4-5	4	4-5	4-5	4-5
CP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CEP	4-5	4-5	4-5	4	4-5	4-5	4-5
OBF	4-5	4-5	4-5	4	4-5	4-5	4-5
OBFE	4	4-5	4-5	4	4-5	4-5	4-5
OBFP	4-5	4-5	4-5	4	4-5	4-5	4-5
OBFEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBH	4-5	4-5	4-5	4	4-5	4-5	4-5
OBHE	4-5	4-5	4-5	4	4-5	4-5	4-5
OBHP	4-5	4-5	4-5	4	4-5	4-5	4-5
OBHEP	4-5	4-5	4-5	4	4-5	4-5	4-5

Table 12
Color fastness to acidic perspiration results of the developed denim fabric samples

Sample notation	Color fastness to perspiration (acidic)						
	Color change	Staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
C	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CE	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBF	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBFE	4	4-5	4-5	4-5	4-5	4-5	4-5
OBFP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBFEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBH	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBHE	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBHP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBHEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5

Table 13
Color fastness to alkaline perspiration results of the developed denim fabric samples

Sample notation	Color fastness to perspiration (alkaline)						
	Color change	Staining					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
C	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CE	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
CEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBF	4-5	4-5	4-5	4	4-5	4-5	4-5
OBFE	4	4-5	4-5	4-5	4-5	4-5	4-5
OBFP	4-5	4-5	4-5	4	4-5	4-5	4-5
OBFEP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBH	4-5	4-5	4-5	4	4-5	4-5	4-5
OBHE	4-5	4-5	4-5	4	4-5	4-5	4-5
OBHP	4-5	4-5	4-5	4-5	4-5	4-5	4-5
OBHEP	4-5	4-5	4-5	4	4-5	4-5	4-5

The results indicate that all samples exhibited excellent color fastness to both acidic and alkaline perspiration, with ratings ranging between 4 (good) and 4-5 (very good to excellent) on the grey scale for both color change and staining. These high ratings suggest that the tested materials effectively resisted color degradation and minimized dye transfer to adjacent fibers under both acidic and alkaline perspiration conditions.

CONCLUSION

In this study, the potential use of hemp fibers in denim fabric structures as a sustainable alternative to traditional cotton was investigated. A total of 12 different denim fabric structures were produced, including reference and hemp-based denim fabrics, as well as flax-based fabrics to enrich the study. Statistical analysis techniques were used to compare the developed denim fabric structures' air and water vapor permeability, antibacterial activity, surface resistance, and fastness characteristics. The findings were as follows:

- The predictive power of the model, expressed by the R^2 value, was found to be 88.26% for air permeability and 88.03% for water vapor permeability, indicating a strong explanatory capacity for these properties. For surface resistance, the R^2 value was determined to be 62.44%, reflecting a moderate level of explanation. These results demonstrate that the model provided a high level of accuracy in predicting permeability characteristics, while its ability to explain surface resistance was somewhat lower, but still acceptable.
- According to the analysis of variance, the most influential independent variable on air permeability and surface resistance was the core component type, while the most influential independent variable on water vapor permeability was the interaction between sheath fiber type *core component type.
- When fabrics without core components were evaluated, unexpectedly, the air and water vapor permeability results of flax and hemp-containing fabrics were found to be lower than those of the reference fabric.
- None of the produced denim fabric structures exhibited antibacterial activity against the test organism *Escherichia coli* (ATCC 25922), a gram-negative bacterium.
- Both flax- and hemp-containing fabrics showed similar fastness properties (light, crocking, laundering, water, and perspiration) to the reference fabrics, meeting industrial standards for all denim types produced.

In conclusion, studies on the use of hemp fibers in denim fabric structures are limited in the literature, and varying results have been reported regarding the tested parameters. In this context, more comprehensive and in-depth research is required.

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